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FLOW-INDUCED VIBRATION OF CIRCULAR CYLINDRICAL STRUCTURES

by

Shoei-Sheng Chen

BASE TECHNOLOGY

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TABLES

NOMENCLATURE

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a	Amplitude of harmonic oscillations
c	Velocity of sound
C_m	Added mass coefficient
c_p	Phase velocity
$[C]$	Damping matrix
C_D (C_L)	Steady drag (lift) coefficient
C_{Dj} (C_{Lj})	Steady drag (lift) coefficient for jth cylinder
C'_D (C'_L)	Periodic fluctuating drag (lift) coefficient
C'_{Dj} (C'_{Lj})	Periodic fluctuating drag (lift) coefficient for jth cylinder
C_s, C_{sj}, C_{sp}	Viscous damping coefficient of a structure
C_v	Viscous damping coefficient
D	Diameter of a cylinder (= 2R)
D_h	Hydraulic diameter
D_o	Diameter of outer cylinder (= $2R_o$)
E	Modulus of elasticity
E_j	Modulus of elasticity for shell j
E_pI_p, EI	Flexural rigidity of cylinder
f	Oscillation frequency
f_f	Natural frequency in fluid
f_s	Frequency of vortex shedding
f_v	Natural frequency in vacuum
f_{fq}	Natural frequency of qth mode in fluid
f_{vj}	Natural frequency of jth cylinder in vacuum
F	Generalized force
g	Fluid force component
g_j	Fluid-force component in the x direction of jth cylinder
g'_j	Fluctuating fluid-force component in the x direction of jth cylinder

g_{sp}	Force per unit length
G	Generalized force or gap
h	Shell thickness
h_j	Fluid-force component in the y direction of jth cylinder or the wall thickness of the jth shell
h'_j	Fluctuating fluid-force component in the y direction of jth cylinder
i	$\sqrt{-1}$
I	Moment of inertia
k	Wave number (= ω/c)
k_s	Spring constant
k_{sj}	Spring constant for cylinder j
k_f	Fluid stiffness
K	Bulk modulus of fluid
K_c	Keulegan-Carpenter parameter
[K]	Stiffness matrix
ℓ	Length or axial wave length
m	Cylinder mass per unit length
m'	$m + m_a$
m_j	Cylinder mass per unit length of cylinder j
m_p	$= m_j$ for $j = 1$ to N and m_{p-N} for $p = N + 1$ to 2N
m_a	Added mass
[M]	Mass matrix
M_d	Displaced mass of fluid or mass of fluid inside a tube
M_c	Mach number
m_p	Displaced mass of fluid per unit length of cylinder j
M_k	Kinetic Mach number
N	Number of cylinders in an array
p	Fluid pressure
P	Pitch

$\{Q\}$	generalized coordinates
r, θ, z	Cylindrical coordinates
$\vec{r}$	Position vector
R	Radius of cylinder (= $D/2$) or radius of curved pipes
R_j	Radius of cylinder j or shell j
Re	Reynolds number
R_k	Kinetic Reynolds number
R_o	Radius of outer cylinder
St	Strouhal number
t	Time
T	Period, axial tension, transverse pitch
TI	Turbulence intensity
u	Cylinder displacement or shell displacement in the axial direction
$\vec{u}$	Velocity vector
u'	Fluctuating velocity component
u_j	Cylinder displacement of jth cylinder in the x direction or axial displacement of jth shell
u_p	$= u_j$ for $p = 1$ to N and v_j for $p = N + 1$ to $2N$
U	Flow speed
$\bar{U}$	Mean flow velocity
$\vec{U}$	Flow velocity ($= u_r \vec{e}_r, u_\theta \vec{e}_\theta, u_z \vec{e}_z,$)
U_r	Reduced flow velocity
v	$= \left(\frac{M_d}{EI}\right)^{0.5} U\ell$ or $\left(\frac{M_d}{EI}\right)^{0.5} RU$, or shell displacement in the tangential direction
v_j	Cylinder displacement of jth cylinder in the y direction or circumferential displacement of the jth shell
V	Volume
x, y, z	Cartesian coordinates
w	Shell displacement in the radial direction

w_j	Radial displacement of the jth shell
α_e	Void fraction
$\alpha_{jk}, \beta_{jk}, \sigma_{jk}, \tau_{jk}$	Added mass coefficients
$\alpha'_{jk}, \beta'_{jk}, \sigma'_{jk}, \tau'_{jk}$	Fluid damping coefficients
$\alpha''_{jk}, \beta''_{jk}, \sigma''_{jk}, \tau''_{jk}$	Fluid stiffness coefficients
$\bar{\alpha}_{jk}, \bar{\beta}_{jk}, \bar{\sigma}_{jk}, \bar{\tau}_{jk}$	Added mass matrices
$\bar{\alpha}'_{jk}, \bar{\beta}'_{jk}, \bar{\sigma}'_{jk}, \bar{\tau}'_{jk}$	Fluid damping matrices
$\bar{\alpha}''_{jk}, \bar{\beta}''_{jk}, \bar{\sigma}''_{jk}, \bar{\tau}''_{jk}$	Fluid stiffness matrices
γ_{pq}	Added mass matrix
δ_s	Scruton's number (mass-damping parameter)
ζ	Damping ratio
ζ_n	Modal damping ratio of the nth mode
ζ_f	Damping ratio in fluid or fluid damping
ζ_v	Damping ratio in vacuum
ζ_{fq}	Damping ratio of qth mode in fluid
ζ_{vj}	Damping ratio of jth cylinder
μ	Viscosity
μ_p	Eigenvalue of added mass matrix
μ_s	Structural damping coefficient
ν	Kinematic viscosity or Poisson's ratio
ν_c	Dimensionless propagation constant
ν_j	Poisson's ratio of the jth shell
ρ	Fluid density
ρ_s	Structure density
ρ_j	Density of shell j
κ	Complex wave number
τ	Dimensionless axial tension
ϕ	Velocity potential function
ω	Circular frequency (= $2\pi f$)

ω_f	Natural frequency in radian in fluid (= $2\pi f_f$)
ω_v	Natural frequency in radian in vacuum (= $2\pi f_v$)
ω_{vj}	Natural frequency in radian of jth cylinder in vacuum
ω_{vpn}	Natural frequency in radian of nth mode of pth cylinder in vacuum
ω_{fp}	Natural frequency in radian of pth mode in fluid
ω_{fpn}	Natural frequency in radian of coupled mode in fluid
$\bar{\omega}_{fj}$	Natural frequency in radian of uncoupled mode of j cylinder
Ω_D (Ω_L)	Circular frequency associated with the drag (lift) forces
Ω_{Dj} (Ω_{Lj})	Circular frequency associated with parameter in the drag (lift) direction
Ω_n	Dimensionless natural frequency of nth mode
ϕ	Flow velocity potential
ϕ_{Dj} (ϕ_{Lj})	Phase angle associated with parameter in the drag (lift) direction
$\phi_n(z)$	Orthonormal function of nth mode
ψ	Flow velocity distribution function

Subscripts

D (L)	Denote drag (lift) direction
f	Denote parameters related to fluid
j,k	Denote cylinder number j,k (j,k = 1 to N)21
m,n,ℓ	0, 1, 2, ... ∞
N	Number of cylinders
p,q	1 to 2N
s	Denote parameters related to structure
v	Denote parameters measured in vacuum

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ABSTRACT

Significant progress has been made in the understanding of vibration of circular cylinders subjected to flow, including development of analysis techniques and experiments on fluid forces, damping, stability boundary, and general structural response. This report summarizes the flow-induced vibration of circular cylinders in quiescent fluid, axial flow, and crossflow, and applications of the analytical methods and experimental data in design evaluation of various system components consisting of circular cylinders.

The information is organized into five general topic areas:

Introduction: Chapter 1 presents an overview of flow-induced vibration of circular cylinders. It includes examples of flow-induced vibration, various fluid force components, and nondimensional parameters as well as different excitation mechanisms. The general principles are applicable in different flow conditions.

Quiescent Fluid: Fluid inertia and fluid damping are discussed in Chapters 2, 3 and 4. Various flow theories are applied in different situations. The main results are the characterization of fluid effects on structural response. Emphasis is placed on isolated cylinders, multiple cylinders and circular cylindrical shells.

Axial Flow: Axial flow can cause subcritical vibration and instability. Chapter 5 summarizes the results for internal flow, while Chapter 6 considers the external flow. Both theoretical results and experimental data are examined.

Crossflow: Different excitation mechanisms can be dominant in different conditions for crossflow. Those include turbulent buffeting, acoustic resonance, vortex excitation, and dynamic instability. Appropriate excitation mechanisms are presented for a single cylinder, twin cylinders, and a group of cylinders.

Design Considerations: Applications of the general methods of analysis in the design evaluation of system components are described and various techniques to avoid detrimental vibration are presented. In addition, available design guides on this subject are discussed.

The results prsented in this report are expected to be useful not only to designers but also researchers in this field.